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Energy Coupling of Nuclear Bursts in and above the Ocean Surface: Source Region Calculations and Experimental Validation

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Energy Coupling of Nuclear Bursts in and above the Ocean Surface: Source Region Calculations and Experimental Validation

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ABSTRACT

In support of the Comprehensive Test Ban, research is underway on the long range propagation of signals from nuclear explosions in the deep underwater sound (SOFAR) channel. Initially our work at LLNL on signals in the source region considered explosions in or above the deep ocean. We studied the variation of wave properties and source region energy coupling as a function of height or depth of burst. Initial calculations on the CALE hydrodynamics code were linked at a few hundred milliseconds to a version of NRL's weak shock code, NPE, which solves the nonlinear progressive wave equation. The simulation of the wave propagation was carried down to 5000 m depth and out to 10,000 m range. We have completed ten such simulations at a variety of heights above and depths below the ocean surface. The results form a so-called "energy coupling curve" of coupled energy versus height or depth of burst. We have derived "starter fields" for calculations on a linear acoustics code which are available to others to extend the propagation to ocean basin distances. More recently we completed calculations to evaluate environmental effects (shallow water, bottom interactions) on signal propagation. We compared results at 25 km range from calculations of the same 1 kiloton burst (50 m height-of-burst) in different environments, namely, deep water, shallow water, and cases with shallow water sloping to deep water. In this shallow water study, we found that propagation through shallow water complicates and attenuates the signal; the changes made to the signal may impact detection and discrimination for bursts in some locations.

We are continuing to make improvements in our understanding our source region signals. Besides the simulations of propagation with bottom interactions referred to above, we are making improvements to our calculational tools and planning small-scale explosive experiments to validate our calculations of source region energy coupling. We have under development a new version of the NPE code which will have improved capability to propagate signals away from the horizontal. We are also planning a series of 1/50-scale (15 lb. HE) experiments in a lake in Wyoming. These experiments, currently scheduled for August 1997, will provide data that can be applied to the full scale. We will present results of the experiments and compare with predictions.

Key words: hydroacoustic, ocean monitoring, underwater signal propagation, energy coupling, NPE, shallow water

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OBJECTIVE:

The planned International Monitoring System will have an ocean monitoring component whose principal function will be to detect and identify clandestine nuclear explosions in the broad ocean areas. The overall goal of our research supported by NN-20 is to increase the understanding of phenomena affecting the ability of the ocean monitoring system to accomplish its task and to establish the long-range signature of large explosions to assist in detection and discrimination wherever the explosion may be, including underwater explosions or explosions in the low atmosphere. Our calculations in the source region for nuclear explosions above and below the ocean surface are part of a continuing effort at Lawrence Livermore National Laboratory to understand how the source region phenomena contribute to the signals which would be detected at ocean basin distances. In particular, we are interested on how much acoustic signal energy will result from a nuclear explosion under various oceanic burst conditions and environments.

The usual analysis of signal propagation from an explosion in (or above) the ocean begins by dividing the ocean into two regions, a region relatively near the burst location—the source region—and another much larger region in which the signal propagation is affected by oceanic conditions such as the bathymetry over thousands of kilometers. Signals in the source region involve high pressures and shock waves near the burst and non-linear wave propagation; the burst height, the ocean depth, and the properties of the bottom materials will all modify the acoustic signals in various ways.

We have completed calculations and analysis for one kiloton explosions in a variety of environments. In previous work we considered bursts in and above a 5000 m deep ocean; more recently we have been evaluating the effects of shallow water and bottom materials on signals in the source region.

RESEARCH ACCOMPLISHED

The initial high temperature, high pressure non-linear phase of our calculations was completed using the LLNL hydrodynamics code CALE (Tipton, 1995). After a time, typically a few hundred milliseconds, the pressures drop to less than 100 atmospheres (10^7 Pa). At this stage the motion was "linked" (transferred) to the weak-shock propagation code, NPE (Nonlinear Progressive wave Equation), developed by Ed McDonald and others at the Naval Research Laboratory[4-6]. With NPE, the calculations can be extended to distances of tens of kilometers (or times of tens of seconds), at which point the near-source-region phase has been completed.

Earlier we completed a set of ten calculations of one-kiloton explosions at various positions in or above the deep ocean. One advantage of beginning our simulations with the deep (5000 m) ocean was the simple geometry. The great depth allowed us to make the approximation that interaction with the ocean bottom was a minor effect compared to the explosion and the development of the main shock wave. With these deep ocean calculations we have made predictions for the amount of energy coupled by an explosion within 1000 m of the ocean surface. The burst location was varied from 1000 m below the surface (fully coupled) to 1000 m above the surface. We compared the total wave energy in the NPE grid at approximately 10,000 m range. (See Figure 1.) This distance was chosen because it was twice the simulated ocean depth. It was expected that when the signal reached this range, the energy coupling and evolution into a deep ocean signal would be essentially complete. The results formed the so-called coupling curve (Fig. 1) for bursts in or above the deep ocean and show that the coupling efficiency declines precipitously as the burst point is raised through the ocean surface. The results from the

ten calculations in the Deep Ocean study are being made available to other contractors in the form of "starting fields" for studies of long range propagation in ocean environments. Some results from this work were reported in the first two references (Clarke, White and Harris, 1995; and Clarke, 1996).

Despite the large decrease in coupled energy for bursts above the ocean surface, we predict that explosions above the ocean surface will produce observable hydroacoustic signals, and that these signals will be unusual for their short duration and relatively low frequency content.

More recent work has focused on simulations of near-source region signals in complex environments; that is, those in which interaction with the ocean bottom is important for the signal propagation. An example might be a burst in or above shallow water, perhaps on or near the edge of the continental shelf. The weak shock wave from a nuclear burst near the surface will interact with the mud, sand or rock in the sea bed fairly quickly, so that the signals that arrive at a given location (e.g. 10 km away) will be strongly affected by the bottom materials. The goal was to evaluate the effects of the water environment (shallow or deep) and the effects of propagation in and attenuation by the mud or rock.

In the past year we have moved from modeling a uniformly deep ocean, to considering simple models of a shallow water environment. We have completed a new set of source region calculations with either a flat or a sloping bottom and a choice of bottom materials. (See summary, Figure 2.) The NPE code was modified to include a sea bed depth that varies with range and which provides for a specification of sound speed gradients in the bottom as well as in the water column. In these simulations, the bottom is modeled with a sound speed profile that corresponds to mud and silt overlying a weak bedrock; an attenuation coefficient of 0.6 dB per wavelength is applied throughout the bottom.

We have completed a series of NPE calculations with the modified code in which waves from the same 1 kiloton burst (50 m height-of-burst) were propagated in water over a flat mud/sand bottom; only the depth was varied from calculation to calculation. We also completed a calculation with a sloping ocean floor and the same bottom materials. The NPE calculations were stopped after propagation for 17 seconds, equivalent to about 25 kilometers, a distance still much smaller than ocean basin distances. Comparing the signals at 17 s, we found that propagation through shallow water complicates and attenuates the signal. The case with the shallowest flat bottom (uniform 200 m depth) showed significant loss of energy, a peak pressure about 10 times lower than the other cases, signal dispersion and a shift toward low frequencies in the spectral shape. All the shallow water cases had more structure in the waves than the deep case. The large loss of energy in the case of a shallow (200 m deep) ocean suggests that there is a "cliff" in the curve of energy transmission versus water depth such that as the water gets gradually shallower at a certain depth the attenuation suddenly becomes much larger so that, at that depth, the transmitted signal suddenly becomes much weaker. Some of the results of this study were discussed at the Informal Hydroacoustic Workshop at the CMR in November 1996, and were included in a recent document (Clarke, Piacsek and White, Dec. 1996)[7]

Work is continuing at LLNL on further NPE calculations of waves propagating downslope in a variety of shallow water and/or littoral environments. At this time, results indicate that a significant fraction of the acoustic energy will generally reach deep water off the continental shelf, although this is strongly influenced by the water depth at the source and the distance of shallow water propagation leading to the shelf. In addition, the strong refraction of the pulse in the upper sea bed layers and the subsequent reradiation into the water column generates head waves that are generally preserved into the deep

water. This feature may potentially serve as a discriminant between seismic and explosive sources and, in the latter case, to characterize the source environment.

With our calculations of signals in shallow water, we are beginning to understand the properties of explosion signals in the near-source region in a variety of environments. The changes made to the signal by propagation through shallow water may impact detection and discrimination for bursts in some locations. As this research develops, our calculations for shallow ocean environments could provide data to create starter fields for long range propagation.

The original formulation of the NPE (Non-linear Progressive Equation) code made the assumption that the signals of interest were propagating at a angle close to the horizontal. This so called "narrow-angle approximation" is a limitation on NPE. Using the CALE hydrodynamics code, which has no such limitation, we have made estimates of wide-angle versus narrow-angle effects on source region signal propagation in the deep ocean. Work is continuing on a newer "wide-angle" version of NPE, which will allow us to evaluate to what degree the narrow-angle limitation has affected our results. If necessary, improved calculations will be completed to provide an adjusted coupling curve, but based on the results from the CALE, the changes are expected to be modest. It is not yet known to what extent the narrow angle limitation has affected the shallow water calculations.

Although we can use computer calculations to model explosion effects and estimate the coupling from detonations above and below the water surface, experimental validation of the modeling results is crucial in the process of refining and extending our modeling capabilities. If our calculations methods can be experimentally validated using small explosions, then scaling relations will allow similar full scale calculations to be applied with some reliability to predict coupling and energy partitioning from large explosions--explosions that are too large to conduct for the sake of model validation. Figure 3 is a summary of our plans for validation of our model calculations.

The Wyoming Field Experiments will attempt to provide source coupling model validation by conducting a number of explosive tests at various depths above and below a body of water. The charge size (15 pounds or 6.82 kg of Pentolite 50/50) will result in an explosion which is at approximately 1/50 length scale (1/125,000 in explosive energy) relative to a one-kiloton nuclear burst. The experiments will take place in an isolated biologically dead lake associated with an abandoned uranium mine in south central Wyoming. A single hydrophone string located about 60 meters from the explosion points will monitor the acoustic energy coupled into the water using 8 piezoelectric sensors spaced from near-surface to about 30m depth. The experimental data will be compared with computer predictions.

CONCLUSIONS AND RECOMMENDATIONS

Validation of source region coupling model calculations is the single most important goal of near-future efforts. In particular, experimental measurements of larger explosions near and below the water surface need to be compared to model calculations. This is necessary to demonstrate the validity of using scaling relations to conduct model validation using small explosions and to test the robustness of the model results in a number of different source regions and scales (Fig. 3). This will be approached in two ways: 1) by taking advantage of events of opportunity such as a series of upcoming ship-shock trials off the coast of Florida by the US Navy and by 2) mining the archived data on old US and French atmospheric nuclear tests over and in the open ocean where hydrophone signal data still exists. Modeling calculations can be run using the same source region and yield to generate acoustic pressure signals that can be compared with actual data.

In summary then, the LLNL research in ocean monitoring will proceed in two directions. We will be continuing calculations of source region signals in a variety of environments to increase our understanding of the effects of shallow water and bottom materials on the signal propagation. In work to validate our modeling calculations, we will be comparing experimental measurements with calculational predictions for explosions at small and large scales.

REFERENCES

1. Clarke, D. B., J. W. White and D. B. Harris, "Hydroacoustic Coupling Calculations for Underwater and Near Surface Explosions," UCRL-ID-122098, Sept. 1995, (U)

2. Clarke, Douglas B., "Pressure Time Histories Derived From Hydroacoustic Coupling Calculations: The Transition to Long Range Linear Acoustics," UCRL-ID-122595, December 1996, (U).

3. Tipton, Robert, "CALE Users Manual, Version 950101," LLNL Internal Report, March 1995. For further information on CALE, contact D. B. Clarke, LLNL, P O Box 808, L-200, Livermore CA 94551. — (510) 422-6593 Email: clarke1@llnl.gov.

4. McDonald, B. E. and W. A. Kuperman, "Time-Domain Solution of the Parabolic Equation Including Non-Linearity," *Comp. and Maths. with Appls.*, Vol. 11, pp. 843-851, Pergamon Press Ltd., UK (1985)

5. McDonald, B. E. and W. A. Kuperman, "Time Domain formulation for pulse propagation including nonlinear behavior at a caustic," *J. Acoustic Soc. Am.*, Vol. 81, pp. 1406-1417 (1987)

6. Ambrosiano, J. J., D. R. Plante, B. E. McDonald and W. A. Kuperman, "Nonlinear Propagation in an Ocean Acoustic Waveguide," *J. Acoustic Soc. Am.*, Vol. 87 (4), p. 1473-1482 (1990).

7. Clarke, D. B., Andrew Piacsek and John. W. White, "Predictions of acoustic signals from explosions above and below the ocean surface: source region calculations," UCRL-ID-125914, CTBT Ocean monitoring Research Deliverable No. H2.2.1, December 1996. (U).

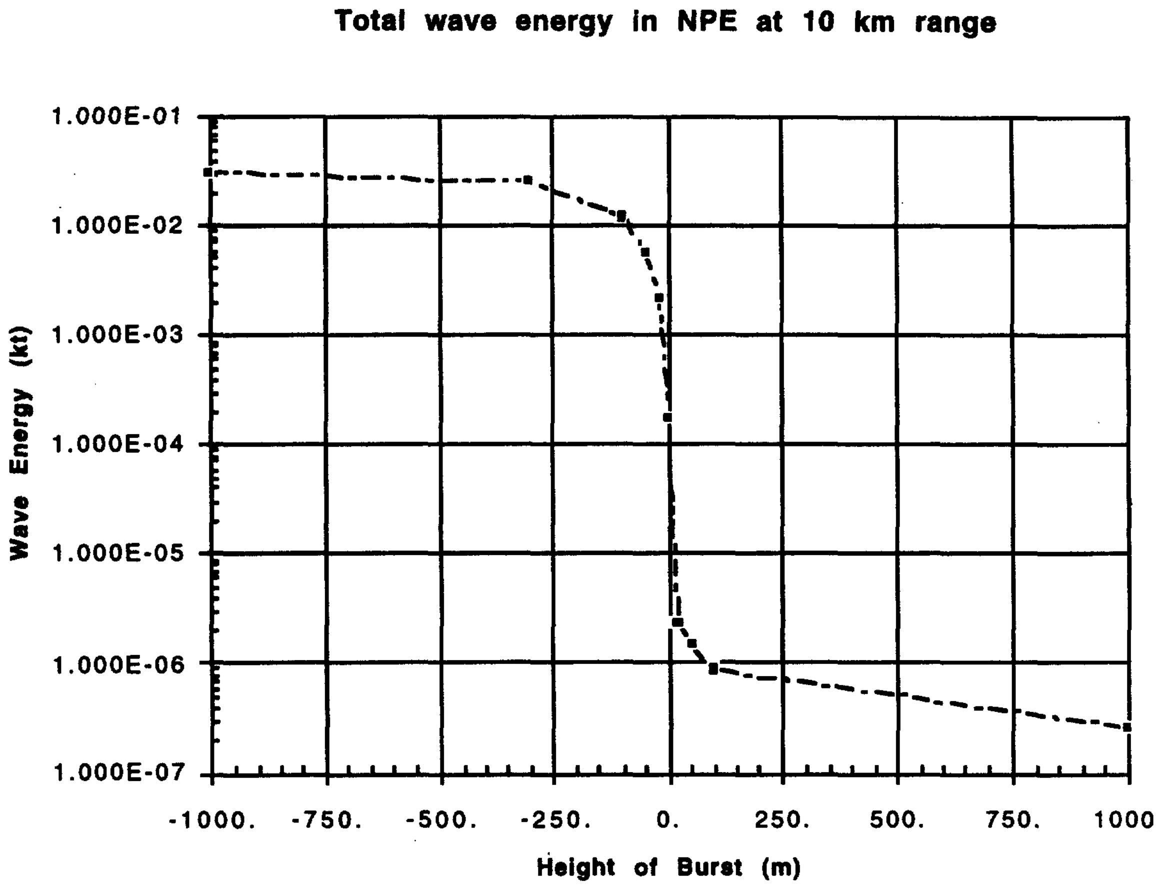

Figure 1. This figure shows results from a series of ten CALE/NPE calculations of one-kiloton nuclear explosions at different heights above (or depths below) the ocean surface. The energy coupled by the explosion at each height is measured by the total wave energy in the water at a range of 10,000 m. The calculated energy coupling is sharply reduced for burst locations near and above the water surface. However, current estimates are that signals from such decoupled explosions are still expected to be easily observable above background noise. At 10 km range, the peak pressures in these simulations range from 100,000 Pa to about 200 Pa.

LLNL Hydroacoustic Calculational projects are moving toward modeling near-source region signals in complex environments

- Initial efforts focused on source region signals for a simple Deep Ocean case (depth = 5000 m)
  - — Major result: Energy Coupling Curve
- Recent work is focusing on environmental effects such as depth near the source region and effects of bottom materials (mud/silt/sand layers)
- Using an enhanced version of NPE with improved treatment of bottom materials, based on work of Ed McDonald, we have completed calculations to study depth and bottom effects
- Compare results at 17 seconds from the same source
  - — Shallow water (flat bottom) 200 m depth, also 1000 m depth
  - — Shallow water, sloping from 200 m to 2200 m over 25 km
  - — Flat bottom, 5000 m deep case, also with bottom materials
- Results show that the ocean bottom configuration has a drastic effect on the pulse leaving the source region, including reduced signal amplitude, dispersion and alteration in spectrum

Figure 2.

Validation of source region coupling model calculations is the single most important goal of near-future efforts

- Planned validation efforts will cover signals from explosions at several scales from under 10 kg HE to large explosions

- Compare experimental measurements of signals with model calculations to
  — Demonstrate the validity of scaling relations
  — Test the robustness of model results in a variety of source regions and scales

- Small scale (1/50) coupling experiments in dead lake in Wyoming
  — 15 lb. HE charges at several locations above or below surface
  — Compare results to calculations (small and full scale)

- Signals from U S Navy ship shock trials (multi-ton HE) near Florida coast (working with BBN)

- Analyze where available the archived data on old atmospheric nuclear tests over and in the open ocean

Figure 3.

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